

Bounds on the Coupling of Light Pseudoscalars to Nucleons from Optical Laser Experiments*

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Abstract

We find the following improved laboratory bounds on the coupling of light pseudoscalars to protons and neutrons: $g_p^2/4\pi < 1.7 \times 10^{-9}$ and $g_n^2/4\pi < 6.8 \times 10^{-8}$. The limit on g_p arises since a nonzero g_p would induce a coupling of the pseudoscalar to two photons, which is limited by experiments studying laser beam propagation in magnetic fields. Combining our bound on g_p with a recent analysis of Fischbach and Krause on two-pseudoscalar exchange potentials and experiments testing the equivalence principle, we obtain our limit on g_n .

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The recent work of Fischbach and Krause in references [1] and [2] has reopened the issue of the laboratory constraints on the Yukawa couplings g of a light pseudoscalar to fermions, defined through the Lagrangian density

$$\mathcal{L}_Y = ig \bar{\psi}(x) \gamma_5 \psi(x) \phi(x) \quad , \quad (1)$$

that couples the pseudoscalar field $\phi(x)$ to the fermion field $\psi(x)$.

It is well known that the exchange of a light ϕ leads to a spin-dependent long-range interaction among fermions. For fermions separated by a distance r , in the limit that the pseudoscalar mass $m \ll 1/r$, the potential is

$$V^{(2)} = \frac{g^2}{16\pi} \frac{1}{M^2} \frac{S_{12}}{r^3} \quad . \quad (2)$$

(We display the formula for the particular case of identical fermions of mass M .) The spin-dependent factor S_{12} of the potential (2) reads

$$S_{12} = 3 \frac{(\vec{\sigma}_1 \cdot \vec{r})(\vec{\sigma}_2 \cdot \vec{r})}{r^2} - (\vec{\sigma}_1 \cdot \vec{\sigma}_2) \quad , \quad (3)$$

with $\vec{\sigma}_i/2$ ($i = 1, 2$) the spins of the two fermions. The laboratory experiments trying to constrain such spin-dependent interaction lead to relatively poor bounds on the Yukawa couplings g to fermions.

In [1,2] the authors have noticed that a significant improvement on the bounds on g for nucleons can be obtained by considering the potential arising from two-pseudoscalar exchange,

$$V^{(4)} = -\frac{g^4}{64\pi^3} \frac{1}{M^2} \frac{1}{r^3} \quad (4)$$

where again we took the $m \rightarrow 0$ limit and the particular case of two identical fermions.

When comparing the potentials (2) and (4) one may think that to consider $V^{(4)}$ would lead to worse bounds since it has a $g^2/4\pi^2$ suppression relative to the potential $V^{(2)}$. However, $V^{(4)}$ is spin independent and thus it is constrained by experimental searches for such new macroscopic forces. Fischbach and Krause have shown that the second effect dominates over the first one when considering Yukawa couplings g_p to protons and g_n to neutrons. In [1], these authors use data from experiments testing the equivalence principle [3]. In [2], they use data from experiments testing the gravitational inverse square law [4]. From the combination of both types of limits they finally get [2]

$$\frac{g_n^2}{4\pi} < 1.6 \times 10^{-7} \quad , \quad (5)$$

$$\frac{g_p^2}{4\pi} < 1.6 \times 10^{-7} \quad . \quad (6)$$

In the present short paper, we would like to show that there are further laboratory constraints on the Yukawa couplings g_n and g_p . We consider the coupling of ϕ to two photons induced by the triangle diagram that we display in the figure. In the loop, the internal line is

a proton since it couples to the pseudoscalar and to the photons. As expected, the evaluation of the triangle diagram leads to a gauge-invariant effective Lagrangian density of the form

$$\mathcal{L}_{\phi\gamma\gamma} = \frac{1}{8} f \epsilon_{\mu\nu\alpha\beta} F^{\mu\nu}(x) F^{\alpha\beta}(x) \phi(x) \quad , \quad (7)$$

with $F^{\mu\nu}(x)$ the photon field strength. One gets [5]

$$f = \frac{\alpha}{\pi M_p} g_p \quad . \quad (8)$$

(M_p is the proton mass).

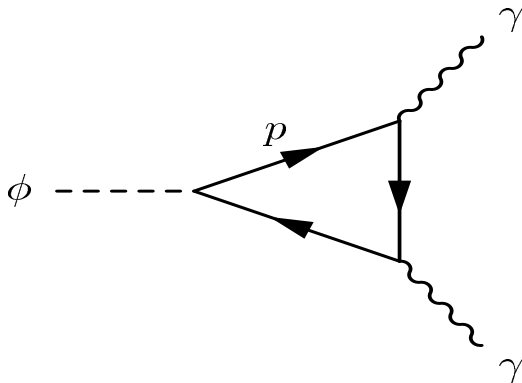


FIG. 1. *One of the two triangle diagrams inducing the effective $\phi\gamma\gamma$ interaction. The other diagram is the crossed one.*

The $\phi\gamma\gamma$ coupling f is suppressed by a factor α compared to the Yukawa coupling g_p but, as shown below, the existing laboratory constraints on f allow us to place a stringent bound on g_p .

Among all the laboratory limits on f [6] the most restrictive ones come from the study of laser beam propagation through a transverse magnetic field. A light pseudoscalar coupled to two photons would induce effects such as optical rotation of the beam polarization, the appearance of ellipticity of the beam, and photon regeneration [7]. The absence of these effects in the data of the experiment leads to the limit [7]

$$f < 3.6 \times 10^{-7} \text{ GeV}^{-1} \quad . \quad (9)$$

Using now the relationship in Eq.(8), the previous limit translates into a bound on the proton Yukawa coupling

$$\frac{g_p^2}{4\pi} < 1.7 \times 10^{-9} \quad . \quad (10)$$

The limit (9) is valid for masses of the light pseudoscalar $m < 10^{-3}$ eV. It follows that our bound (10) is also valid for this mass range. This corresponds to interaction ranges of the potentials (2) and (4) larger than about 0.02 cm.

We can now constrain the neutron Yukawa coupling by combining our bound (10) with the results from [1]. As explained above, constraints on g_n and g_p can be placed by considering the $V^{(4)}$ potential. In reference [1], the implications for the couplings g_n and g_p from the equivalence principle experiment [3] have been worked out in detail. The final result is a constraint on a combination of both Yukawa couplings [1]

$$(9.6g_p^2 + 15.3g_n^2)|0.05925g_p^2 - 0.05830g_n^2| < 6.4 \times 10^{-13} \quad . \quad (11)$$

Introducing (10) in (11) we find the stringent bound

$$\frac{g_n^2}{4\pi} < 6.8 \times 10^{-8} \quad . \quad (12)$$

The ongoing experiment PVLAS [8] that also studies laser beam propagation is supposed to ameliorate the present limit (9) on f . This will in turn improve our bounds (10) and (12).

In summary, we have shown first that the stringent bound in Eq.(10) on the coupling g_p of the proton to a light pseudoscalar (with $m < 10^{-3}$ eV) can be obtained by considering the induced coupling of the pseudoscalar to two photons which in turn is limited by laser propagation experiments. Second, we have combined our bound on g_p with the results coming from data on equivalence principle experiments constraining the spin-independent potential due to two-pseudoscalar exchange. As a result, we are able to put the stringent bound in Eq. (12) on the neutron coupling g_n to the light pseudoscalar.

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